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Structure, dynamics and evolution of disk galaxies in a hierarchical formation scenario

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Abstract. Using galaxy evolutionary models in a hierarchical formation scenario, we predict the structure, dynamics and evolution of disk galaxies in a ΛCDM universe. We find that the Tully-Fisher relation (TFR) in the I and H bands is an imprint of the mass-velocity relation of the cosmological dark halos. The scatter of the TFR originates mainly from the scatter in the dark halo structure and, to a minor extension, from the dispersion of the primordial spin parameter λ. Our models allow us to explain why low and high surface brightness galaxies have the same TFR. The disk gas fractions predicted agree with the observations. The disks formed within the growing halos have nearly exponential surface brightness and flat rotation curves. Towards high redshifts, the zero-point of the TFR in the H band increases while in the $B-$band it slightly decreases.

1. The method

We have developed a new method to study disk galaxy formation and evolution. Our purpose is to model self-consistently the structure, dynamics, and luminous properties of a disk galaxy as well as its evolution. At the same time, we want to predict correlations and statistical distributions of the disk galaxy population.

In our scenario of disk galaxy formation and evolution:

- the disk in centrifugal equilibrium forms inside-out within a growing dark matter (DM) halo with a rate of gas accretion proportional to the rate of cosmological mass aggregation (e.g., Gunn 1982; Ryden & Gunn 1987; Avila-Reese & Firmani 1997; Avila-Reese, Firmani, & Hernández 1998),
- the DM halos acquire angular momentum by cosmological torques,
- the star formation (SF) in the disk is triggered by gravitational instabilities and it self-regulates through an energy balance in the interstellar medium (ISM).

We assume (i) spherical symmetry and adiabatic invariance during the gravitational collapse of the DM, (ii) spin parameter λ constant in time and with a

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lognormal distribution, (iii) aggregation of baryon matter to the disk in form of gas (no mergers), (iv) detailed angular momentum conservation and adiabatic invariance during the gas collapse, and (v) stationary self-regulated SF only in the disk. According to our galaxy evolutionary model (Firmani, Hernández, & Gallagher 1996), the disk vertical structure is sustained against gravity by the turbulent pressure produced by the SNe and gas accretion kinetic energy injection. The balance of this energy input with the turbulent energy dissipation *in the disk* self-regulates the SF. The efficiency of SF in this model almost does not depend upon mass of the system, and the disk-halo feedback is assumed to be negligible; this is because the disk ISM is a dense and very dissipative medium and gas and energy outflows are confined in a region close to the disk.

The properties of the models depend on four initial factors: total virial mass M_v, mass aggregation history (MAH), spin parameter λ, and fraction of M_v that is incorporated into the disk, f_d. The MAHs are calculated with the extended Press-Schechter formalism (Avila-Reese et al. 1998), the λ's are extracted from a lognormal distribution, and f_d is fixed to 0.05. We use a flat ΛCDM model with $\Omega_\Lambda = 0.65$, $h = 0.65$, $\sigma_8 = 1$.

2. Results

In Firmani & Avila-Reese (1999a), the above method was used to calculate catalogs of galaxy models through Monte Carlo simulations. The main results are:

• A diversity of halo density profiles were obtained, the most typical one being close to that suggested by Navarro, Frenk & White (1997). Our density profiles agree rather well with those obtained in cosmological N-body simulations (Avila-Reese et al. 1999).

• The disks present a nearly exponential stellar surface density distribution. The stellar surface density (surface brightness, SB) strongly depends on λ, and less on mass and MAH.

• For a given f_d, the shape of the rotation curves is more peaked for higher SB (smaller λ), but in general, the shapes are nearly flat for most cases. If f_d is too high ($\gtrsim 0.08$), the rotation curves of disks with small λ ($< \lambda_{\min} \approx 0.04$) are too peaked, and these disks are probably unstable. If f_d is too small ($\lesssim 0.03$), then low and high SB galaxies will have very different TFRs, contrary to observations.

• The rotation curve decompositions show a dominance of the DM component down to the very central regions for most of the models with $f_d \approx 0.05$. This occurs because the inner density profile of the DM halos are steep ($\rho(r) \propto r^{-1}$). When we introduce a shallow core in our DM halos —proportional to the one inferred from the rotation curves of low SB galaxies—, the disk component of the rotation curve dominates the central regions of high SB (normal) galaxies.

• The slope and zero-point of the $I-$ and $H-$band TFRs are an imprint of the mass-velocity relation of the cosmological CDM halos. We find that the TFR is almost independent of the assumed f_d, when the disk component in the rotation curve decomposition is non-negligible ($f_d \gtrsim 0.03$ for the cosmological model used here). We find that the scatter in our TFR originates *mainly from the scatter in the DM halo structure (related to the MAHs)* and, to a minor extension, from the dispersion of λ. The predicted scatter does not disagree with the observational estimates.

• The TFR for high and low SB models is approximately the same, and the slope of the correlation among the residuals of the TF and luminosity-radius relations is small and non-monotonic, although the shape of the rotation curves of our models correlates with the SB. For a given total (star+gas) disk mass, as the SB decreases, the maximum rotation velocity, $V_{\max}$, of the models decreases, *but*, owing to the dependence of the SF efficiency on the disk surface density, the stellar mass M_s (luminosity) also decreases. This combined influence of the SB (λ) on $V_{\max}$ and M_s produces that models of different SB fall in the same $M_s - V_{\max}$ relation. As the result, high and low SB models present a similar TFR. This also explains why the λ contribution to the scatter in our TFR becomes so small.

• Our models and the observations show that the disk gas fraction ($f_g = M_g/(M_g + M_s)$) indeed strongly correlates with the SB: as SB increases, f_g decreases. Moreover, our gas fractions agree very well with the observational estimates given in McGaugh & de Blok (1997).

• The slopes of the $H-$ and $B-$band TFRs remain almost constant until high redshifts. For a fixed $V_{\max}$, the stellar mass ($H-$band luminosity) of the models at $z \approx 1$ is smaller than at $z = 0$, while, due to luminosity evolution (SF history), L_B is slightly larger (see Firmani & Avila-Reese 1999b). Therefore, the observed evolution of the TFR in the B band should not be used as equivalent of the evolution of the stellar mass-velocity relation ($H-$band TFR).

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